1973

Pilot study on the fatigue of tensile specimens, PHASE i, June 1969

R. J. Smith

S Lozano

P. Marek

Low Cycle Fatigue

A PILOT STUDY ON THE FATIGUE OF TENSILE SPECIMENS

PHASE I

by

Raymond J. Smith

Salvador Lozano

Paul Marek

This work was conducted as part of a study of low-cycle fatigue, sponsored by the Office of Naval Research, Department of Defense, under Contract N 00014-68-A-514; NR 064-509. Reproduction in whole or part is permitted for any purpose of the United States Government.

Department of Civil Engineering

Fritz Engineering Laboratory
Lehigh University
Bethlehem, Pennsylvania

June 1969

Fritz Engineering Laboratory Report No. 358.1

TABLE OF CONTENTS

ABSTRACT

Twenty-eight tension specimens were tested to gain experience and initial information on the significance of several design factors which may influence the low-cycle life of A514 steel under cyclic loading.

The failure mode and the correlation with maximum stress and stress range was observed.

It was suggested to test a supplemental series of simple tension specimens to confirm the observation and to complete factorials for the statistical evaluation.

1. INTRODUCTION

This report presents the results of a pilot study, which is one phase of a major research program designed to provide information on the behavior and design of joined structures under low-cycle fatigue.

The purpose of this preliminary pilot study, Phase I, is to gain experience and initial information on the significance of several design factors which may influence the life of A514 steel under cyclic loading. The design factors of major interest in this phase are the effects of maximum applied stress, S_{max} and applied stress range, S_r and the behavior of the proposed specimen configuration.

A study of previous investigations has indicated that most low-cycle fatigue tests are strain controlled. However, the tests of the pilot study were performed at a constant load amplitude.

A discussion of the testing procedure, the test results, and the specimen failure surfaces are presented. A detailed evaluation of the test data will have to be supported by further experimentation.

2. EXPERIMENTAL PROGRAM

2.1 Experiment Design

An experiment design was undertaken to permit rational evaluation of the influence of the controlled variables on the specimen fatigue lives. The objective of the proposed factorial, as shown in Table 1, was to evaluate the significance and interaction of the controlled variables. In Table 1, S_{max} is the maximum applied stress and S_r is the applied stress range. The magnitudes of S_{max} and S_r were selected on the basis of previous studies [1] and corresponded to fatigue lives up to an estimated 100,000 cycles.

Due to the variation in test results associated with fatigue data each cell of the factorial contained three specimens to provide replication. This replication of specimen within each cell provides a measure of the error variation and increases the sensitivity of the factorial.

In addition supplemental tests were conducted to explore the response outside the range of the factorial.

2.2 Test Specimens

Phase I of the preliminary pilot study consisted of testing 26 specimens of A514 Grade J steel. The specimens were flame-cut from the flanges of two beams previously tested in high-cycle fatigue in another project, designated as Project 334. The positions on the flanges of the beams from which most of the specimens were obtained did not correspond to the areas of either high applied stress or high residual stress (shear spans). These specimens were not prepared and the machined edges were not smoothed. The specimen configuration is shown in Fig. 1 and the section properties are listed in Table 2. In Table 2, b is the width, t is the thickness, and A is the area of the specimen.

The two beams from which the specimens were cut were obtained from Project 334. They were designated PWC 311 and PWC 152. PWC 311 was subjected to 2.37 million cycles of loading and PWC 152 was subjected to 0.40 million cycles of loading. Since the tension specimens were cut from the shear span, the stress varied linearly along the length of flange. It is estimated that the specimens were subjected to average stresses that varied from -5 to 16 ksi in beam PWC 152 and from 7 to 16 ksi in beam PWC 311. The two beams were manufactured from the same heat. The mechanical properties of these beams, obtained from simple tension tests, are given in Table 3. In Table 3, σ_p is the proportional limit, σ_{yd} is the dynamic yield stress using a strain rate of 0.025 in./min., σ_u is the ultimate stress, and E is Young's Modulus. Figure 2 shows a stress-strain curve traced from a simple tension test on a PWC 152 specimen. The specimen configuration for the simple tension test was that shown in Fig. 1.

2.3 Testing Machines

The fatigue tests were conducted in a 200 Kip Universal Amsler Testing Machine. The Amsler machine applies the alternating load, by hydraulic means, to the specimen by gripping it with a set of cross-cut jaws.

The simple tension tests were performed in a 120 Kip Tinius Olsen Testing Machine.

2.4 Testing Procedure

The specimen was placed in the Amsler machine grips in such a way as to minimize the eccentric loading effect. After the specimen was placed, it was loaded statically to a maximum stress that to be used in the fatigue test. This seated the grips against the specimen and thus prevented slippage during the testing. Thereafter the alternating load was applied to the specimen until the desired maximum applied stress and range of applied stress were obtained. The frequency of the alternating load was set at either 250 or 500 cycles per minute depending on the expected number of cycles to failure. The number of cycles were accumulatively recorded by a counter on the Amsler machine. Counting started only after the designated applied stress range was reached. This would take anywhere from 400 to 1000 cycles to achieve and are not included in the data. The Amsler machine was then set to detect an approximately ten percent decrease in load as a criterion for failure, and to stop the machine. This load decrease was caused by either an increased flexibility of the cracked specimen or by shock due to a sudden crack even after the specimen failed. The number of cycles between failure and the coming to a stop of the machine was observed to range from 400 to 600 cycles. These cycles were included in the data because they equal approximately the number of cycles needed for the adjustment of the desired stress range at the beginning of the test.

The order of testing the specimens was randomized to prevent systematic errors and bias due to uncontrolled variables. All specimens were tested under normal room temperature conditions.

3. RESULTS AND DISCUSSION

Table 4 presents a summary of the number of specimens tested in each cell. The specimens in the cell marked with an asterisk were ones in which the maximum applied stress was 102 ksi. This applied stress resulted from keeping the applied stress range constant at 99 ksi while the minimum obtainable stress due to the loading arrangement was 3 ksi.

The fatigue test data is presented in Table 5. The specimen notation was derived from the beam designation system of Project 334. In Table 5, S_{max} is the maximum applied stress and S_r is the applied stress range. The number of cycles to failure and the approximate location of the crack for each fatigue specimen are also given. Figure 3 defines the approximate region of failure. For some specimens the number of cycles to failure were low as compared to other specimens of the same cell. These low values may have resulted from the effects of either initial flaws such as weld repairs, inclusions, crack from previous cyclic load history, or misalignment of the specimen in the machine grips.

The number of cycles to failure for specimens within individual cells as well as over the entire range may have been affected by the number of low-stress cycles undergone previously as portions of the flanges of high-cycle fatigue beams. Failure may have been influenced also by the stress concentrations produced by the specimen configuration. For most specimens stress concentrations are evident because fractures were predominantly in the region of the machined radius of the specimen as indicated in Table 5.

Table 6 categorizes the cells and gives a brief description of the fracture surface for each category. In the categories of S_r values between 62 ksi and 75 ksi there was a change in the fracture made. At an applied stress range of 75 ksi and greater, only a few specimens showed a small area of crack propagation before failure resulted. This behavior occurred without reaching the yield stress on the net area of the specimen. However, specimens tested at an S_r of 62 ksi and less, exhibit larger areas of crack propagation accompanied by some necking of the specimen before failure. Consequently, it is possible that there exists some relationship to be further investigated.

This change in failure mode was observed to be most significant for the series of tests at S_{max} equal to 112 ksi. The series of tests for S_{max} equal to 100 ksi was not extended far enough into the lower applied stress ranges.

Crack arrest marks on the specimen surfaces indicated that the Amsler machine did not maintain the maximum load during rapid crack extension. However visual observation of specimens and load indicated that this had little effect on the number of cycles to failure.

Figure 4 summarizes the data in Table 5, in the form of a plot of the logarithm of the number of cycles to failure N_f versus the logarithm of the applied stress range S_r. It is visually apparent that the transformation of life and stress may result in an approximate linear relationship between these two variables.

It is apparent from Fig. 4 that the number of cycles to failure of specimens tested at a maximum applied stress of 90 ksi is about the same as specimens tested at 100 (or 102) ksi when the stress range was the same. Hence, stress range apparently accounts for nearly all the variation in cycle life.

When the maximum stress S_{max} was increased to 112 ksi, the test data tended to shift to the left of the data for other levels of maximum stress. An examination of Fig. 4 shows that this observation is not clear at all levels of stress range. At both the 75 and 99 ksi levels of stress range, specimens at a maximum stress of 100 ksi had comparable lives. However specimens which showed this behavior apparently have reduced fatigue lives due to other defects. The data suggests that at applied stress levels above the proportional limit the maximum applied stress may have some influence upon the expected number of cycles to failure. This behavior is contrary to the results of high-cycle low stress fatigue where the maximum applied stress has usually no effect upon the number of cycles to failure and so should be verified by further tests.[12]

As was expected from high-cycle fatigue behavior, the applied stress range had a substantial effect upon N_f. For an increase in the S_r value, a decrease in the number of cycles to failure was observed.

4. RECOMMENDATIONS

Table 7 suggests a supplemental series of simple tension specimens. The new series of tests, Phase II, is proposed to explore further the following:

1. Further evaluation of the effect of S_{max} and its interaction with stress range, S_r, when S_{max} is less than the proportional limit σ_p. This study has indicated that S_r may have accounted for all the variation in cycle life when S_{max} was less than or equal to 100 ksi.

2. Effect of maximum stress and stress range on the failure mode. Particular emphasis will be given to the cases of S_{max} equal to 100 ksi and S_r equal to 62 ksi and to S_{max} equal to 112 ksi and S_r equal to 62 and 52 ksi.

3. The evaluation of the effect of maximum stress S_{max} above the proportional limit and the establishment of the boundary at

which the maximum applied stress shifts the S-N curve.

4. The evaluation of the effect of maximum stress above the yield stress σ_y using the previously applied stress ranges. It is expected that this maximum applied stress will further shift the S-N curve and may provide information on the influence that plastic strains exhibit in low-cycle fatigue.

5. The testing of specimens with attached strain gages to allow observation of strain history to failure. During these tests useful experience should be gained in recording and observing plastic strain increments in the Amsler Testing Machine.

6. To perform a statistical evaluation of the results after the second phase of the tests has been completed.

5. ACKNOWLEDGEMENTS

This paper presents the results of an experimental pilot study of the fatigue of tensile specimens. The investigation is one phase of a major research program designed to provide information on the behavior and design of joined structures under low-cycle fatigue.

The investigation was conducted at Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pennsylvania. The Office of Naval Research, Department of Defense, sponsored the research under Contract N 00014-68-A-514; NR 064-509. The program manager for the overall research project is Lambert Tall.

The guidance of, and the suggestions from, the members of the special Advisory Committee on Low-Cycle Fatigue is gratefully acknowledged. The authors are indebted to John W. Fisher, Lambert Tall, and Benjamin T. Yen for their help during the testing program and thanks are due also to Alan W. Pense and Morton Perlman who provided fruitful discussion and comments.

Sincere thanks are due to Miss Joanne Mies who typed the report, to Jack M. Gera who prepared the drawings, and to Kenneth Harpel, lab foreman, and his staff, for their assistance during testing.

Lynn S. Beedle is Director of Fritz Engineering Laboratory, and Joseph F. Libsch is Vice-President for Research, Lehigh University.

6. NOMENCLATURE

S_{max}	=	Maximum Applied Stress (ksi)
S_r	=	Applied Stress Range (ksi)
σ_{yd}	=	Dynamic Yield Stress using a strain rate of 0.025 in./min.
σ_u	=	Ultimate Stress (ksi)
E	=	Young's Modulus (ksi)
σ_p	=	Proportional Limit (ksi)
N	=	Number of Cycles to Failure

7. TABLES AND FIGURES

S_r \ S_{max}	90	100	112
75	3	3	3*
87	3	3	3
99		3	3

*Number of Specimens in Cell.

Table 1. Proposed Factorial - Phase I

Specimen No.	b (in)	t (in)	A $(in)^2$
311- 1	2.008	0.380	0.763
311- 2	2.009	0.380	0.763
311- 3	2.010	0.380	0.764
311- 4	2.009	0.380	0.763
311- 5	2.010	0.379	0.762
311- 6	2.010	0.380	0.764
311- 7	2.010	0.379	0.762
311- 8	2.010	0.380	0.764
311- 9	2.011	0.380	0.764
311-10	2.008	0.380	0.763
311-11	2.007	0.380	0.763
311-12	2.009	0.380	0.763
311-13	2.010	0.379	0.762
311-14	2.010	0.380	0.764
311-15	2.009	0.380	0.763
311-16	2.008	0.380	0.763
311-17	2.008	0.380	0.763
311-18	2.009	0.380	0.763
152- 1	2.004	0.392	0.786
152- 2	2.007	0.395	0.793
152- 3	2.006	0.394	0.790
152- 4	2.006	0.391	0.784
152- 5	2.005	0.392	0.786
152- 6	2.006	0.390	0.782
152- 7	2.005	0.394	0.790
152- 8	2.005	0.393	0.788
152- 9	2.005	0.394	0.790
152-10	2.005	0.394	0.790

Table 2. Section Properties.

Specimen No.	σ_p (ksi)	σ_{yd} (ksi)	σ_u (ksi)	E (ksi)
PWC-152-10	101.3	113.9	119.1	27900
PWC-311-9	104.8	114.8	119.2	28400

Table 3. Material Properties.

S_r \ S_{max}	90	100	112
42			1
52			2
62			1
75		3	3
87	3	3	3
99		3*	3
109			1

*S_{max} = 102 ksi.

Table 4. Completed Tests - Phase I.

Specimen Number	S_{max} (ksi)	S_r (ksi)	Number of Cycles to Failure (KC) (250 cycles/min.)	Location of Fracture
311-12	90	87	77.5	End
311- 5	90	87	63.1	End
311- 4	90	87	63.7	End
152- 7	100	75	139.5	End
152- 5	100	75	135.3	End
152- 2	100	75	75.2	End
152- 9	100	87	76.3	End
152- 4	100	87	84.8	Center
152- 1	100	87	62.0	Center
152- 8	102	99	56.9	End
152- 6	102	99	35.9	End
152- 3	102	99	23.9	End
311-11	112	42	732.8*	End
311- 7	112	52	271.0*	End
311- 3	112	52	116.3*	Center
311- 6	112	62	127.2	End
311- 2	112	75	94.6	Center
311-15	112	75	92.1	End
311-10	112	75	71.1	End
311-17	112	87	49.7	End
311-18	112	87	48.2	End
311-13	112	87	47.8	End
311- 1	112	99	31.8	End
311-16	112	99	39.0	End
311-14	112	99	43.8	End
311- 8	112	109	22.4	End

*Frequency of alternating load = 500 cycles/min.

Table 5. Summary of Data.

S_r \ S_{max}	90	100	112
42 52 62			Extensive necking. Clear initiation crack. Sharp change to rough texture. Arrest marks visible but close spaced on outer fibers. Internal delamination. Generally flat fracture.
75		No extensive necking, well developed flat initiation crack, then 45° fracture fine textured delamination.	Some necking. Multiple initiation, smaller cracks. Generally 45° fracture. Wide spaced arrest marks. Some surface cracking not at fracture. Rough delamination.
87 99 109	No extensive necking, 45° fracture after small flat initiation crack. Delamination at crack tip.	Some necking of specimen. Initiation not well developed. Greater delamination roughness, coarser at center. Flat, then 45° fracture.	Necking about same as above. Initiation sites small, not clear. Rough coarse delamination. Generally 45° fracture.

Table 6 - Fracture Appearance of Fatigue Specimens.

S_{max} / S_r	80	90	100	106	109	112	115
52						3	
62		3	3			3	
75	3	3	X*	3	3	X	3
87		X	X	3	3	X	3
99			X			X	
109						3	
112							3

*X - Completed Cells

Table 7. Proposed Factorial - Phase II

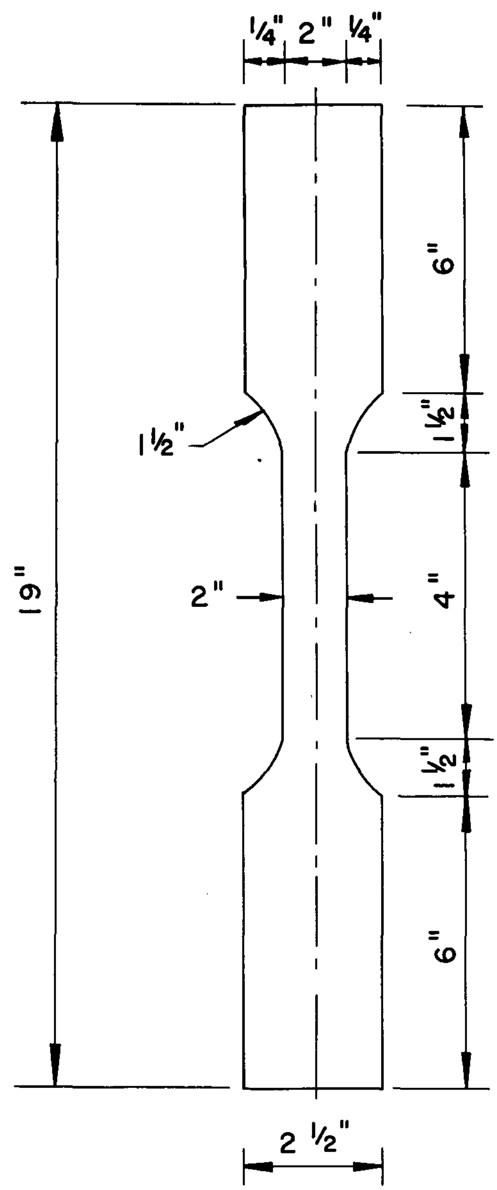

Fig. 1 The Shape of the Specimen.

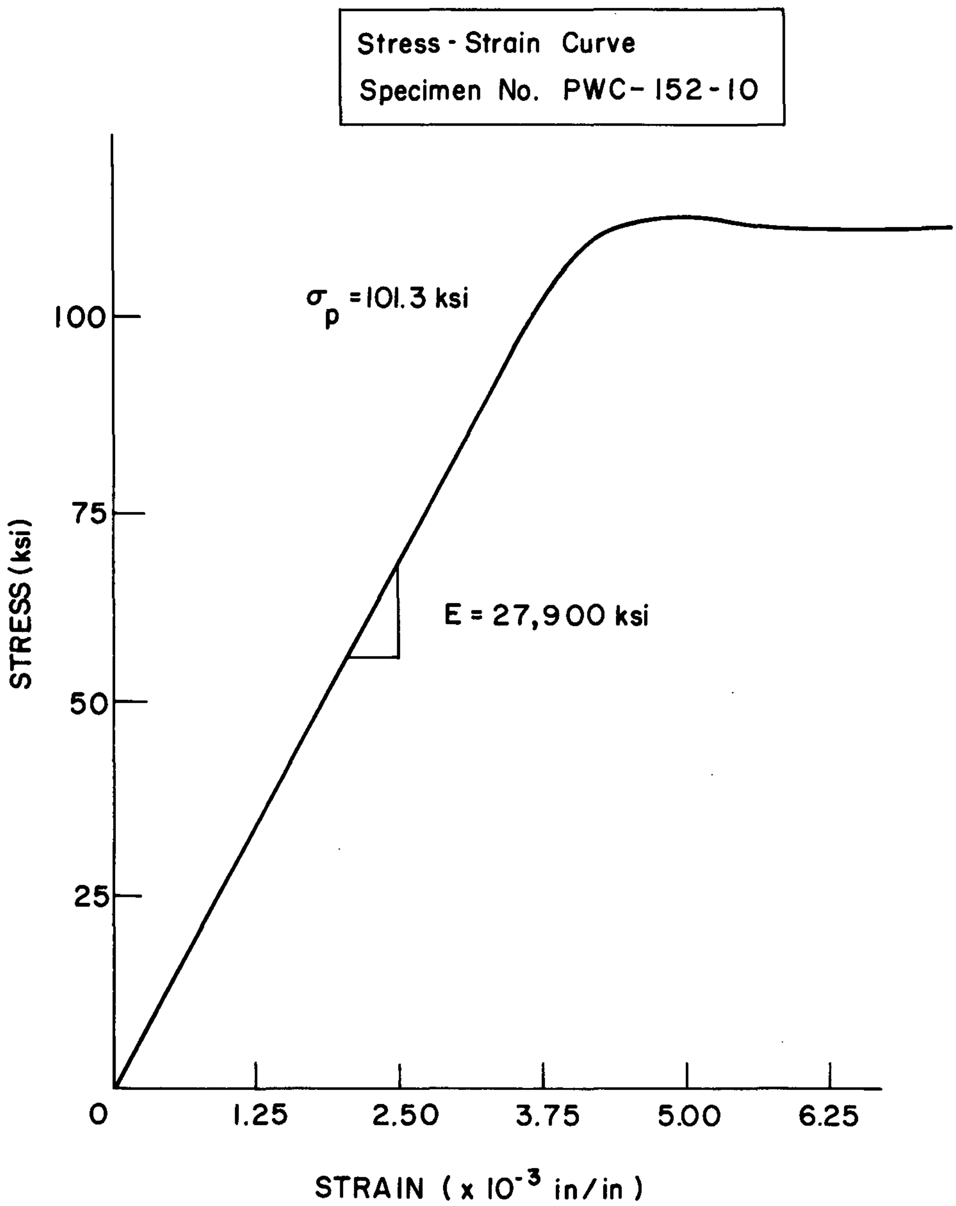

Fig. 2 The Stress-Strain Curve.

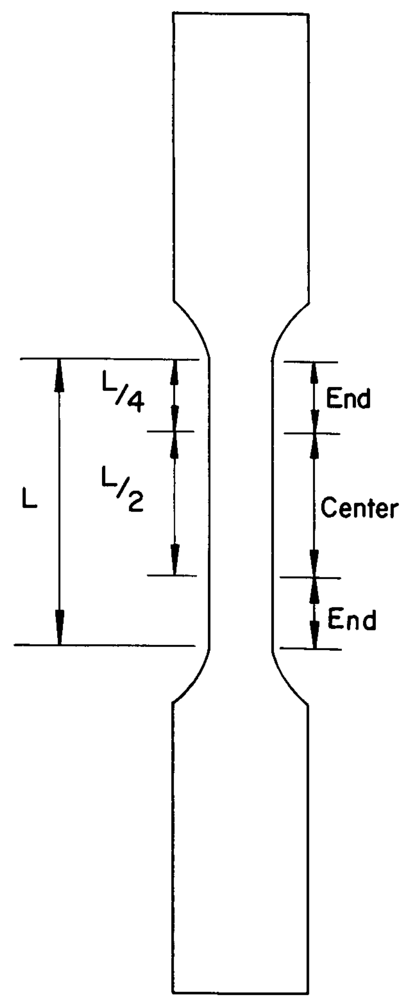

Fig. 3 Region of Failure.

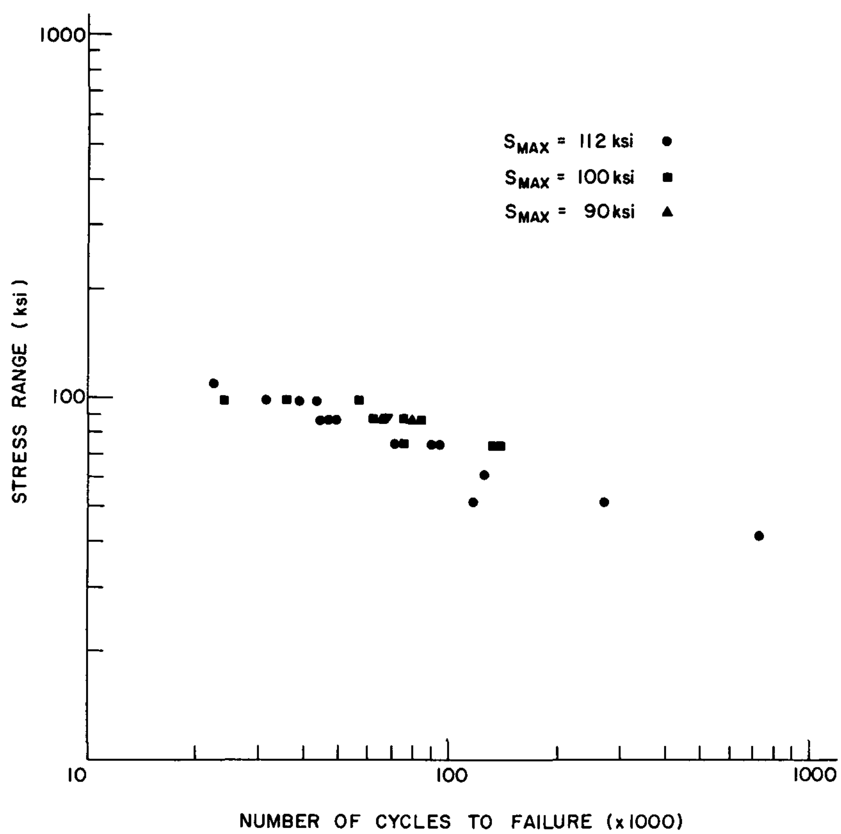

Fig. 4 Stress Range Versus Number of Cycles.

8. REFERENCES

1. J. Dubuc
EFFECT OF MEAN STRESS AND OF MEAN STRAIN IN LOW CYCLE FATIGUE OF A-201 AND T-1 STEELS, Report to Pressure Vessel Research Committee, Ecole Polytechnique, Montreal, Canada, July, 1967.

2. K. H. Frank and J. W. Fisher
THE FATIGUE STRENGTH OF WELDED COVERPLATED BEAMS, Fritz Laboratory Report 334.1, March, 1969.

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
	2b. GROUP

3. REPORT TITLE

Low Cycle Fatigue
A PILOT STUDY ON THE FATIGUE OF TENSILE SPECIMENS-PHASE I

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*

Raymond J. Smith, Salvador Lozano, Paul Marek

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1969	28	2

8a. CONTRACT OR GRANT NO. N 00014-68-A-514; NR 064-509	9a. ORIGINATOR'S REPORT NUMBER(S) 358.1
b. PROJECT NO. 358	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

Twenty-eight tension specimens were tested to gain experience and initial information on the significance of several design factors which may influence the low-cycle life of A514 steel under cyclic loading.

The failure mode and the correlation with maximum stress and stress range was observed.

It was suggested to test a supplemental series of simple tension specimens to confirm the observation and to complete factorials for the statistical evaluation.